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Advanced Optical Sources for Deep-Space Data Transmission Applications

Submitted by

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Introduction

With the eventual goal of landing humans on Mars in mind, NASA has launched an extensive program for developing communication technologies that can transmit data between Earth and Mars at a bit rate high enough to provide real-time video in addition to other capabilities. Microwave transmitters can achieve, at best, a bit rate of only 10 to 20 Mb/s across interplanetary distances. For this reason, attention has focused on free-space optical communication systems that have the potential of achieving data rates as high as 10 Gb/s between geostationary satellites and earthbound receivers. However, the deployment of such systems at Mars has to overcome several practical issues [1]. The biggest challenge is the huge loss of power in the received signal at Earth as the optical signal spreads over a distance of some 400 million km between Mars and Earth. It has been estimated that a free-space optical communication system transmitting from a geostationary satellite would suffer up to 80 dB of additional loss if it were located on the surface of Mars and its bit rate would be limited to at most 100 b/s [1].

The current NASA plan is to develop the Mars Telecom Orbiter (MTO) and use it to demonstrate the feasibility of optical communication through a Mars Laser Communications Demonstration (MLCD) System [1, 2]. It will be launched in 2009 and it will carry a free-space optical communications system designed by a research team made of scientists at the Massachusetts Institute of Technology (MIT) Lincoln Laboratory and the Jet Propulsion Laboratory (JPL). The team aims to overcome the signal attenuation problem with a new pointing/tracking system, optimized telescope and modulation systems, error-correction coding, and photon-counting detectors. With these advances, Earth's first deep-space, free-space optical communications systems seems to be feasible. However, the initial data rate may not be high enough, and there is naturally great motivation to increase it.

Objective and Goals

In this proposal we present a novel concept and use it to develop an advanced optical source that may overcome the beam spreading to a large extent. Using current optical sources, a data pulse sent from Mars has a spot size of about 1000 km by the time it reaches Earth, owing to beam spreading by diffraction, if we assume a beam size of 30-40 cm at the transmitter end. This huge increase in the beam size forces one to transmit a large amount of energy in each pulse to ensure that at least one photon is captured by the receiving antenna on Earth. If diffraction can be controlled, one can increase the bit rate and use lower-power transmitters. Also, with improved lasers it should be possible to reduce pulse duration to the picosecond range, which would enable one to increase the data rates by a factor of thousand or more. We plan to develop high-power fiber lasers capable to emitting such sort pulses with high peak power levels. In addition, we would develop a beam-control module, designed to reduce beam spreading as the data is transmitted across a distance of 400 million km. In the following sections, we describe in detail our approach designed to meet these objectives.

Fiber Laser Development

Pulsed light sources based on optical fibers are light-weight, compact, robust, and efficient. In recent years the performance of lasers based on fiber-gain media has improved dramatically. Continuous-wave lasers that produce kilowatts of powers now exist, and ultrashort-pulse fiber amplifiers that produce approximately 100 watts of average power have been demonstrated. On the other hand, the demonstrations of high-power pulsed fiber amplifiers are feasibility demonstrations, more akin to physics experiments than integrated device concepts. Nevertheless, it is clear that in the near future, fiber lasers will outperform solid-state lasers in many applications.

The MIT Lincoln lab and JPL teams have already tentatively chosen to use an amplified fiber laser for the light source in a free-space communication system. The most likely candidate is the combination of ytterbium (Yb) fiber laser and amplifier that emits near 1.06 μm. A Mach-Zehnder lithium-niobate modulator, external to the laser, will be used to modulate the laser output and create a pulse train. The resulting transmitter will generate pulses 1-10 ns in duration, with peak and average powers of 300 and 5 W.

Low light levels available at the detectors currently limit the achievable data rate of free-space communication systems. Even with an extremely low divergence (a few microradians) of the currently proposed optical sources, photon-counting detection will be required. Information will be encoded on the pulse train with a pulse-position modulation scheme that will require 30 to 40 dB of extinction from the modulator. This level of performance is near the limit of achievable extinction with the best devices, and may even require the use of two modulators in series.

The use of our proposed beam-control module will increase the power available at the detectors, which will in turn enable higher data rates. Thus, it appears that sources of high-energy and high-contrast optical pulses with repetition rates of gigahertz and above will be needed. Considering these parameters, sources based on mode-locked lasers should be investigated. Mode-locked lasers are capable of producing pulse trains with much higher extinction ratios than can be obtained with external modulation. These high-contrast pulse trains can be amplified to pulse energies well above those proposed for the MLCD system. In particular, recent advances in short-pulse fiber lasers and amplifiers are quite pertinent to the needs of deep-space communications. Pulse energies as large as millijoules, and pulse durations ranging from the nanosecond range to the femtosecond range will be possible. The performance can be optimized to the needs of the communication system.

The first stage of the pulsed source will be a mode-locked fiber laser. Such a laser can produce pulses between 100 fs and 10 ps in duration, simply by varying the group-velocity dispersion experience by each pulse traveling inside the cavity. Even longer pulses can be generated by active mode-locking. Shorter pulses ultimately will allow higher data rates, but will also be more susceptible to dispersion; narrow-bandwidth, and thus long-duration, pulses may be desired for systems that require significant propagation through atmosphere. Extinction ratios of 80 dB are obtained with femtosecond and picosecond lasers [3], and mode-locked fiber lasers with repetition rates near 1 GHz have achieved 60-dB suppression of secondary modes [4]. Mode-locked fiber lasers emitting at 1 μm based on Yb-doped fiber have been demonstrated in the last couple years. These are extremely stable and reliable devices. In fact, fiber lasers have demonstrated the lowest amplitude and phase noise of any short-pulse oscillator. Fiber lasers with repetition rates around 100 MHz can produce pulses with energy up to ~10 nJ, and the pulse energy decreases at higher repetition rates. In any case, the output will be amplified to reach the energies needed for transmission. Amplification adds noise and complexity, so oscillators that generate high pulse energies will be desired, to minimize the needed gain. The recently demonstrated self-similar lasers [5] may be advantageous for this purpose – they can achieve pulse energies approximately an order of magnitude greater than previous short-pulse fiber lasers. Furthermore, another order-of-magnitude increase in pulse energy is theoretically possible. Thus, self-similar fiber lasers should produce ~100-nJ pulses.

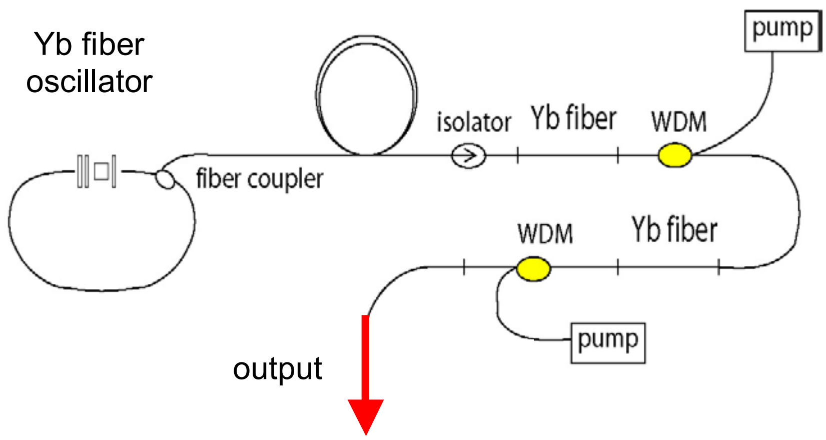

Figure 1. Schematic of short-pulse fiber amplifier. Such a device will be capable of reaching microjoule pulse energies.

Amplification of the pulses from an oscillator to the needed microjoule energies should be relatively straightforward. A schematic is shown in Figure 1. At these energy levels, nonlinear distortion of the pulse is just beginning to become an issue with large-mode-area fibers. Large-mode-area photonic crystal fiber supports single-mode propagation with mode-field diameters up to ~40 μm, with negligible coupling to higher-order modes and therefore excellent beam quality. It is possible to dope such fibers with Yb and use them for making fiber lasers. Figure 2 shows the cross section of a Yb-doped photonic crystal fiber. Amplification at the 1-μm wavelength also benefits from the presence of normal dispersion in fiber; the combination of normal dispersion and positive Kerr nonlinearity allows a pulse to grow in energy without distortion or breakup of the pulse. The pulse may accumulate bandwidth and a frequency chirp, but it will be stable. Under these conditions, self-similar pulse evolution also occurs. This pulse propagation is illustrated in Figure 3. Self-similar fiber amplifiers capable of emitting 25

W of average power and 5 MW of peak power have been demonstrated at a 50-MHz repetition rate, and these results are very promising in the present context.

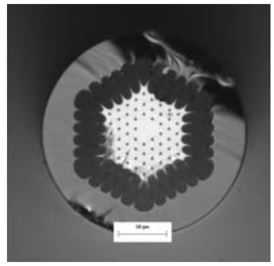

Figure 2. Cross-section of large-mode area Yb-doped photonic crystal fiber.

High-average power (>1 W) fiber sources must be built with double-clad fiber, to accommodate high-power but low-brightness diode lasers. Double-clad fiber is an excellent solution for continuous-wave and long-pulse lasers. However, the use of double-clad fiber typically increases the required fiber length by an order of magnitude, which is a major disadvantage for sources of pulses with duration nanoseconds and below. We expect that semiconductor lasers based on quantum-dot gain media (under development by Deppe and co-workers and discussed later in this document) will have a substantial impact here. In addition to the major benefit of radiation hardness, these lasers should reach 5-10 W power levels in a single-mode output in the next few years. These pump lasers will enable the use of short, single-clad gain fibers, which will reduce the complexities that arise from excessive nonlinearity that currently dominate the design of short-pulse fiber sources.

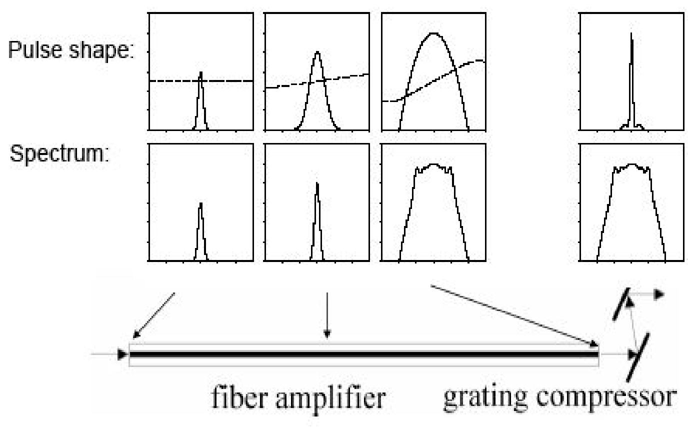

Figure 3. The concept of self-similar amplification of a pulse in the presence of strong nonlinearity is shown. The spectrum broadens, and the pulse acquires a frequency chirp (indicated as the dashed line across the pulse shape), but the pulse does not break up. The chirp is nearly linear, so the pulse can be dechirped to the Fourier-transform limit with a dispersive delay.

The practical benefits of fiber-based instruments have already been recognized: ultimately, the devices will be all-fiber, with light never leaving the waveguide, and will also be insensitive to environmental perturbations such as temperature changes and mechanical stress. It will be possible to integrate fiber devices into the structure of aircraft or spacecraft. They will occupy total volumes much less than 1 m^3, and will have electrical-to-optical energy efficiencies of ~25%. Our industrial colleagues at Clark/MXR, Inc. (Dexter, MI) have a decade of experience with commercial short-pulse fiber lasers. In laboratories, these instruments operate for years without any maintenance, and it is reasonable to expect that they could be space-qualified.

Quantum-Dot Pump Lasers

Deep-space applications of fiber lasers will require highly reliable, high efficiency diode laser pumps. Diode lasers can obtain greater than 60% electrical to optical power conversion, and when properly designed can efficiently couple this power into a fiber to create a high efficiency, high power fiber laser source. These fiber laser sources are a leading candidate for deep space communication. However the most commonly used diode lasers for high efficiency fiber pumping, 980 nm planar quantum well devices, are also susceptible to radiation-induced defects. Radiation-induced defects cause nonradiative recombination centers that in a planar quantum well active material lead to rapid defect growth and laser diode failure. In planar quantum wells, the defect growth occurs because local suppression of the carrier density due to fast recombination at the defect site causes excess current flow into the defect site, in turn causing local heating and eventual thermal runaway as the dislocations loops grow. Therefore the susceptibility to radiation-induced defects is an inherent property of the planar quantum well active material geometry.

In contrast, a new laser diode technology based on nanostructured active materials that form quantum dots (QDs) has an inherently different behavior that results from 3-dimensional quantum confinement. The 3-dimensional quantum confinement suppresses diffusion currents, and therefore the defect growth from radiation induced damage. Indeed, initial experiments have shown that QD lasers are inherently less susceptible to radiation-induced defects [6, 7]. Although QD lasers have been demonstrated for a wide range of wavelengths, the best performance has been obtained using InAs nanostructures grown on GaAs to produce QD laser diodes that operate between 900 nm and 1.3 μm. This wavelength range is especially attractive for many space applications, especially the 980 nm wavelength used for laser diode pumping of high efficiency, high power fiber lasers.

Although the prospect of creating radiation hard laser diodes is important in itself, the 3-dimensional quantum confinement also gives rise to other very desirable properties for high power lasers. QD lasers exhibit a reduced alpha-factor as compared to planar quantum wells, which is a key parameter controlling both spectral and beam quality. The lower alpha-factor means that there is less coupling between the optical gain and its contribution to the cavity refractive index, and therefore less of a tendency for QD lasers to exhibit filamentation. Since high power laser diodes can be limited by catastrophic facet damage, increasing the stripe width while retaining single transverse mode operation could increase the power level coupled from QD laser diode pumps into single mode fibers. The improved transverse mode stability also benefits from the reduced carrier diffusion that comes from 3-dimensional quantum confinement. Another potentially important aspect is that QD laser diodes exhibit very low internal losses, as low as 2 cm^{-1}, so that longer cavity lengths may be possible for high power QD lasers. Again this can increase the single mode power levels for efficient fiber coupling. And finally, the QD laser has been shown to be inherently less temperature sensitive, so that reduced cooling may be possible to increase the overall efficiency of laser diode-pumped high power fiber laser sources.

While QD laser diodes have only been in existence since 1994, they are undergoing rapid development in laboratories around the world. The inherent physics of the QD active material that can lead to radiation hardness, high beam quality, and decreased temperature sensitivity can make it the most important laser diode technology for space applications. Preliminary works from researchers associated with NL Nanosemiconductor have already shown impressive high power demonstrations for QD laser diodes operating at wavelengths between 1.0 and 1.3 µm. An example of these results is shown in Fig. 4 for a 6 W InAs QD laser operated CW at 20°C [8]. These power levels show that QD laser diodes can be useful for diode pumping of high power fiber lasers.

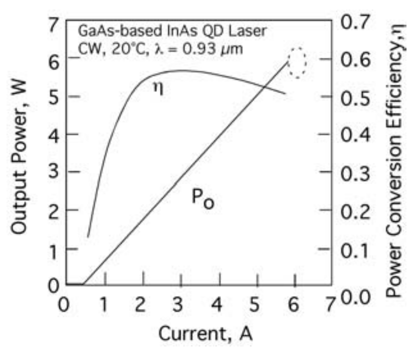

Fig. 4. Power vs. current curve for a 0.93 µm GaAs-based InAs QD laser with a 100 µm emitting aperture and 1 mm cavity length is shown. The open circle shows the point at which catastrophic facet damage occurs. The power conversion (wall-plug) efficiency reaches 58% at ~2 W with a maximum power level of 6 W obtained from the device (From Ref. [3]).

Along with high power, enhanced beam properties have also been demonstrated by the nanosemiconductor researchers using QD laser diodes and standard fabrication techniques. This enhanced beam quality of QD laser diodes is very important for high power applications for the reasons given above. The impressive improvement is clearly demonstrated in direct comparison with planar quantum well laser diodes based on the same fabrication technique. Figure 5 shows these experimental results for near field patterns from either planar quantum wells or QD laser diode active materials. Both types of lasers have 10 µm stripe widths. QD laser diodes with active regions operating at either 1.1 µm or 1.3 µm exhibit single intensity spot near-fields that fill the emitting aperture, while the planar quantum well laser material shows a broadened and irregular near field due to carrier spreading and filamentation.

That QD laser diodes can operate at much lower threshold current densities with much lower internal waveguide losses that enable longer cavity lengths, and exhibit improved mode stability, indicate that when optimized these devices can surpass planar quantum well lasers in their high power performance. When these traits are coupled with the dramatic improvement in radiation hardness and high temperature operation, it's clear that the QD laser diodes are highly suited for a wide variety of space applications, including fiber laser pumping.

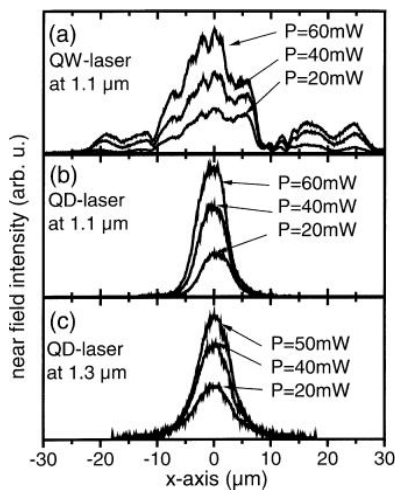

Fig. 5. Near field intensity plots from QD laser diodes and planar quantum well laser diodes fabricated by researchers associated with NL Nanosemiconductors with otherwise similar device structures with 10 μm width. Both at 1.1 μm and 1.3 μm the QD laser diode exhibits stable mode operation at the same power levels for which the planar quantum well device exhibits filamentation. The stable beam characteristics of the QD laser diodes are due to the lack of carrier diffusion that results in spatial hole burning, and a reduced alpha factor.

Figure 6 illustrates the electronic structure of self-organized epitaxial QDs, along with important processes controlling QD laser diode performance. The 3-D quantum confinement that leads to truly discrete electron-hole orbitals, and electronic localization, is the source of the radiation hardness and high temperature operation. Electrons and holes captured in the QDs rapidly relax to the thermal distributions within the individual QDs. The energy separations between electron levels, given by $E_{1,c} - E_{1,v}$ in Fig. 4, can reach 100 meV in optimized structures, and electrons are therefore thermalized into the ground state electron levels. Because of valence band heavy and light hole mixing however, the hole levels are only on the order of 10 meV and suffer thermal broadening of the hole occupation due their close energy spacings. Until 2002 this thermal hole broadening limited the high temperature performance of QD laser diodes, when the UT research team recognized its importance and proposed p-type modulation doping to "flood" the QDs with holes and ensure their ground state occupation even at high temperature [9]-[11]. The inclusion of p-type modulation doping on QD laser diodes has been carried out at the telecom important wavelength of 1.3 μm, with a dramatic enhancement in high temperature performance, including high temperature modulation.

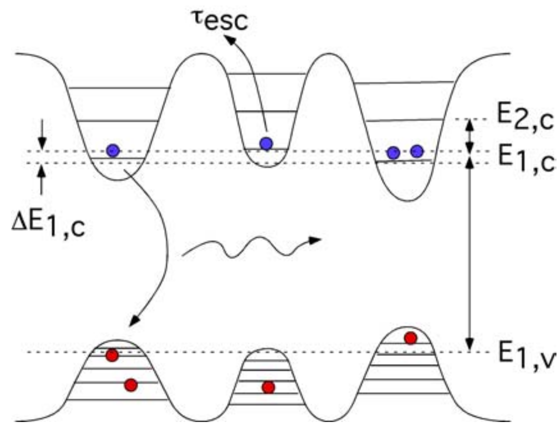

Fig. 6. Schematic illustration of the electronic energy structure of the self-organized QDs. Electrons and holes are trapped in 3-D quantum confined islands producing discrete electron and hole orbitals with ground state recombination that occurs with high efficiency. The hole levels are much closer in energy than electron levels, and size variation in the QDs produces inhomogeneous broadening of the radiative transitions.

The UT team of this proposal first demonstrated the superior high temperature performance for GaAs-based QD laser diodes using a five QD stack active layer, but NL Nanosemiconductor made an important further improvement by increasing the number of QD stacks to ten. Their p-doped QD device approach was sent to several leading laboratories around the world working on QD laser diodes to verify the superior high temperature performance.

From Fig. 6, the key QD parameters controlling the temperature sensitivity, once p-modulation doping is introduced into the QD active material, are the depth of the potential wells, the energy separations of the discrete electron energy separations, the filling of the electron levels needed for lasing threshold, which is set by the QD density, and inhomogeneous broadening. These parameters set the electron escape time and limit diffusion in the QD active material. These parameters also set the radiation hardness that also tracks electron confinement.

In order to utilize these inherent benefits of the QD active material, we will develop an approach to high power QD laser diodes that can enable highly reliable operation at high powers and over wide operating temperatures with high efficiency, as well as providing spectral control of the lasing mode. The new device structure is based on an all-epitaxial and nearly planar design that provides both mode- and current-confinement, as shown in Fig. 7. The device structure uses an epitaxial regrowth over a GaAs mesa region adjacent to an AlGaAs region formed on the p-side of the device. The GaAs mesa forms a conductive path into the QD active region for hole injection, while at the same time forming a lateral index step within the cavity to confine the optical mode in a self-aligned manner. Low temperature grown GaAs layers further confine the current away from the current injected region, but these do not influence the optical confinement and only serve to eliminate any parasitic currents due to the nearly planar device structure. The source of the current confinement on the p-side in the AlGaAs region outside the GaAs mesa is due to Fermi level pinning at the regrown crystal interface, which is absent on the GaAs mesa. A similar technique has been developed for low threshold VCSELs [12], and electrical and optical measurements on both VCSELs and initial edge emitting QD lasers show that both the current confinement and optical confinement are excellent, while the optical confinement is readily engineered through choice of the mesa material and height.

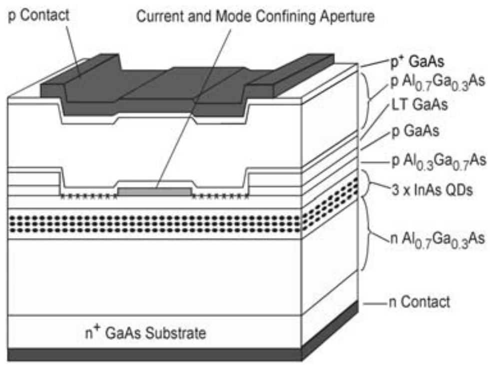

Fig. 7. Schematic illustration of the all-epitaxial QD laser approach to be pursued to obtain high reliability over a wide operating range of temperatures is shown.

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The merits of this new approach for high power QD laser diodes for space applications made possible by the electronic confinement of the QD active material are quite important for high reliability over a wide operating range of temperatures and include:

1) A nearly planar, strain-free all-epitaxial approach with no regrowth or impurity diffusion with the QD active material to give high reliability over a wide operating range of temperatures.

2) Simultaneous mode- and current-confinement capable of low threshold operation and high beam stability.

3) Lithographically defined for highly reproducible fabrication of QD laser diodes and diode arrays.

4) Lithographically defined to allow intracavity longitudinal gratings for lateral control of injection current density and index profile to maximize lateral overlap of gain and mode profiles, and lateral gratings can be introduced to control spectral and spatial beam coherency.

Item 4) on the list above can make a key advance in high power lasers that exhibit excellent beam quality and wavelength stability at high temperature. This is especially important for laser diode pumps that otherwise require some temperature stabilization for efficient fiber pumping. To understand how longitudinal gratings can improve beam stability, we return to the near-field intensity pattern of Fig. 5. It's apparent that elimination of lateral diffusion currents coupled with a low alpha-factor can lead to beam stability. On the other hand, the current injection is still uniform in the 10 µm wide stripes and does not match the lateral intensity profile of the lasing mode. This problem, which is somewhat subtle and can not be easily solved in planar quantum well laser diodes because of lateral diffusion currents, can be solved using QD active materials and a chirped longitudinal grating along the stripe of the QD laser diode. Perfect matching between the lateral gain profile and optical mode, by controlling the lateral current density as well as the lateral refractive index, can potentially increase the QD laser diode near-field width to ~15 µm, while simultaneously decreasing the threshold current. The low internal loss of the QD laser waveguide, which can be on the order of 2 cm^{-1} , then allows for drive currents in excess of several amps, and output powers from single stripes in excess of 1 W into single lobes. This feature will be particularly important to produce QD laser diodes with excellent beam quality for high power fiber coupling.

Initial QD results at University of Texas based on the cavity design of Fig. 7 have produced a relatively low threshold current of 26 mA and a low current density of 260 A/cm^{-2} for a 10-µm stripe width. Drive currents of over 1.4 A are possible in the initial devices, even with the low values of threshold current and ~2 mm long cavities. Extending the cavities to longer lengths can lead to output powers of several watts from a single transverse mode QD laser diode operating at ~980 nm.

Diffraction Control

We propose to develop a beam-control module that would be attached to the output of fiber laser for producing low-divergence beams. The aim is to reduce the beam divergence below the "standard diffraction limit" so that the source is better suited for deep-space communications. This may sound counterintuitive. However, one should keep in mind that a large number of techniques have been developed for terrestrial fiber-optic communication systems for controlling dispersion of optical pulses inside optical fibers [13]. The underlying paraxial wave equations governing dispersion of optical pulses in fibers and diffraction of optical beams in free space are identical. It is thus possible that one may be able to discover a suitable "diffraction management technique" that would reduce the beam size at the earth considerably.

It is well known that Maxwell's equations have specific solutions representing beams that do not spread much beyond their initial size [14]-[19]. An example is provided by the Bessel beams [14]. When the intensity distribution of an optical beam is in the form of a zeroth-order Bessel function, the beam propagates without any spreading in free space. Unfortunately, an ideal Bessel beam cannot be used for data transmission in practice because such a beam requires an infinite amount of power (all Bessel functions have an oscillatory structure that extends to infinity in the transverse dimensions). However, it should be possible to tailor the amplitude an optical beam such that it has a finite power level but it still mimics the properties of the Bessel beams approximately. In fact, a whole class of such beams, known as X waves, has been discovered [15]-[19]. In some cases, such beams do spread in free space but at a rate much lower than that experienced by Gaussian and other finite-size beams.

We propose to investigate and develop novel techniques for realizing limited-diffraction spreading optical beams for applications to deep space communications. One possibility is to modify the phase front of beams emitted by existing optical sources using spatial light modulators. Although phase modulation has not attracted much attention in the context of X waves, we believe it has the potential for NASA space applications. The other possibility is to modify the coherence properties of an optical source in combination with phase modulation and produce sources that emit beams with controlled diffraction. Another approach would be to develop devices whose diffractive properties are opposite of those of free space [20]. One can then implement a diffraction-management scheme in a fashion analogous to that used for modern fiber-optic communication systems [13].

This project will meet two of NASA's challenge problems in the CCEI element of the Advanced Space Technology Program, under the theme of Space Communications and Networking: (1) Space Backbone Networks and Space Wide Area Networks and (2) Laser Sources and Active Sensors. The resulting technologies will provide high power, high efficiency, radiation-hardened transmitter components for advanced, reliable deep-space laser communications. Therefore they will (a) support emerging spectrum allocations in the optical regimes for Lunar/Mars human and robotic mission applications and (b) benefit high-bandwidth optical communication links. This project addresses all three critical measures of R&D success, namely, reliability, effectiveness and affordability. By providing components for reliable space communications, this project addresses three of the Strategic Technical Challenges: 1) "ASARA" Human Presence in Deep Space, 2) Data-rich Virtual Presence and 3) Margins and Redundancy.

The impact of the proposed technology on NASA's future plans will be substantial as optical sources developed under this project will allow data transmission at higher bit rates. Because of reduced beam spreading, they will allow more power to reach the receiver. We expect such a source to be useful for most deep-space communication applications.

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